

GRBS FROM WEAKLY-MAGNETIZED, SLOWLY-ROTATING STARS IN BINARIES

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RESUMEN

Utilizando evolución estelar de sistemas binarios (con transferencia de masa Caso C) el espín de varios agujeros negros (ANs) en binarias de rayos X ha sido predicho, observaciones posteriores han confirmado al menos tres de estas predicciones. La energía rotacional de éstos ANs es suficiente para producir destellos de rayos gama (GRBs) largos acompañados por explosiones de hipernova (HN) y aún así dejar un AN de Kerr. No obstante, campos magnéticos intensos y/o dínamos en el interior de la estrella progenitora del AN pueden extraer toda la reserva de momento angular en el núcleo estelar previniendo la formación de un colápsar. Esto es, aún en binarias capaces de formar ANs de Kerr, la mayor parte de la rotación del AN puede venir del manto estelar, lo cual produce un largo retraso entre la formación del AN y la adquisición de su espín. Este escenario descartaría a estas binarias como posibles precursoras de GRBs.

En este trabajo se realiza un estudio sobre las condiciones necesarias para que las progenitoras de ANs de Kerr en binarias de rayos X puedan producir GRBs. Escalas de tiempo de sincronización por fuerzas de marea y de Alfvén son comparadas para campos magnéticos de diferentes intensidades en estrellas de He. Se efectúa una búsqueda para un rango de campos magnéticos que permitan sincronización por fuerzas de marea hasta el núcleo estelar pero que prevengan la fuga de momento angular durante las subsiguientes etapas de rotación diferencial. Se estima también el costo energético de la producción de un campo magnético durante el colapso gravitacional que permita la formación de un GRB. Finalmente, se encuentra un rango de parámetros congruente con observaciones.

ABSTRACT

The spin of a number of black holes (BHs) in X-ray binaries (XBs) has been predicted (and, in at least three cases, confirmed by observations) by using a binary stellar evolution model with Case-C mass transfer. The rotational energy of such BHs is sufficient to power up (long) gamma-ray bursts and hypernovae (GRBs/HNe) and still leave a Kerr BH behind. However, strong magnetic fields (B fields) and/or dynamo effects in the interior of a BH-progenitor star may be capable of rapidly depleting the angular momentum from the stellar core, hence, preventing the formation of a collapsar. Thus, even if binaries can produce Kerr BHs, most of their rotation is acquired from accreting the stellar mantle, with a long delay between the formation of the BH and its spin up. Hence, not being good sources of GRBs.

We study the necessary conditions to produce GRBs by the progenitors of such BHs. Tidal-synchronization and Alfvén timescales are compared for B fields of different intensities threading through He stars. We search for a B-field range which allows tidal spin up all the way into stellar core but prevents its slow down during differential rotation phases. Energetics for producing a strong B field during core collapse, which allows for GRB central engines, are also estimated. An observationally-reasonable choice of parameters is found.

Key Words: binaries: general — black hole physics — gamma-ray bursts: general — stars: evolution — stars: magnetic field — stars: massive

1. INTRODUCTION

Massive stars, those capable of leaving a massive core which may collapse into a black hole (BH) tend to lose a substantial amount of mass through winds. The material leaving the star is at the surface, where most of the angular momentum of the star resides. Thus, wind mass loss implies substantial spin angular momentum loss to these stars. If the magnetic field is considerable at the stellar surface and beyond, the lever arm increases further helping the spin down. Furthermore, evolution into

the giant and supergiant branch drastically increases the radii and the wind mass loss. Hence, evolved stars lose most of the angular momentum left in the star after the main sequence. This picture is enhanced by metallicity, as wind-mass loss is increases along with it.

Long gamma-ray bursts (LGRBs) are thought to be the product of a massive, rapidly-rotating, gravitationally-core-collapsing (GCC) star. During GCC said stars collapse first from the poles as no centrifugal force prevents the material from falling. This clears the way for jets to propagate along the rotational axis of the star as a lower density region, and lower resistance path is created. It is also likely that during GCC differential

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rotation ensues and any fossil magnetic field becomes entwined forming magnetic towers with their axis coinciding with the rotational one. Therefore, further helping the jet stay focused to drill its way out of the star.

In (Lee et al. 2002) a binary model is proposed where angular momentum is injected back into the stellar core at the very last hour. This is done with the idea that little angular momentum will be lost at that stage even if large wind-mass-loss rates prevail. Plus the orbit will still be a large reservoir of angular momentum for the spin (considering an orbit which does not become too wide from the little mass loss that may still occur). For binaries with Case C mass transfer (after He core burning), a common envelope phase will follow. This allows for the orbital separation to shrink at the expense of removing the H outer shell of the star. As the companion star approaches the He core of the supergiant, the density increases and, eventually, the later is again confined to its shrunken Roche lobe, thus, ending the common envelope phase. The core of the supergiant, now, likely a Wolf-Rayet (WR) star, still fills a substantial portion of its Roche lobe nonetheless. From the tidal-synchronization timescales estimated in Zahn (1975) and Zahn (1977), which depend on a high power (6 to 8.5) of the ratio (a/R) (a being the orbital separation and R the stellar radius) it can be shown (see, e.g., van den Heuvel & Yoon 2007) that the massive star will synchronize with the orbit within its remaining lifetime before GCC.

Using this model, Lee et al. (2002) have correctly predicted the spin of three BHs in X-ray binaries (XBs). These were measured and reported in Shafee et al. (2006) and Steiner et al. (2011). Using this model, and the estimated BH spins, Brown et al. (2007) and Moreno Méndez et al. (2011), have estimated the energies available from spin for a BH to function as a GRB central engine in the known LMXBs (low-mass XBs). These results show that most local LMXBs have too much energy and thus are likely to blow apart the accretion disk feeding the central engine too quickly. Thus, they are likely candidates to explain subluminal LGRBs with very energetic hypernovae, but not Cosmological GRBs. Instead, LMC X-3, may be a more likely candidate for a Cosmological GRB as argued in Brown et al. (2008). There exist three BHs in HMXBs with very large spins (Liu et al. 2008; Gou et al. 2009, 2011). If these massive BHs ($10 - 20M_{\odot}$) were born with these spins the energy stored in them is several times 10^{54} to 10^{55} erg. These formation of these BHs would have likely disrupted the binary had they had such energy available at that time. It is highly likely the spins of these BH were acquired after GCC, however this assumption also carries difficulties (Moreno Méndez et al. 2008; Moreno Méndez 2011).

Layer Composition	Mass [M_{\odot}]	Radius [R_{\odot}]	Density [g cm^{-3}]
He	5	10^{11}	$\frac{3}{4\pi}10^4$
C-O	10	10^{10}	$\frac{6}{4\pi}10^7$
Fe	1.5	10^8	$\frac{9}{4\pi}10^9$

TABLE 1

TOY MODEL OF A PRE-CORE-COLLAPSE
HELIUM STAR OF $16.5M_{\odot}$. LOOSELY BASED ON
THE MASS RATIOS IN FIG. 33.1 OF
Kippenhahn & Weigert (1990)

Woosley (2011) and Woosley & Heger (2012) suggest that magnetic torques will spin down the core of the massive star as it differentially rotates after it shrinks to start a new burning stage. This would prevent the star from becoming a collapsar and, thus, from being a GRB progenitor.

2. THE COLLAPSAR MODEL AND THE BLANDFORD-ZNAJEK MECHANISM

In the Collapsar model, the Fe core of a star collapses, fails to launch a supernova (SN), and forms a BH acquiring a fraction of the angular momentum. The material along the rotational axis falls directly in a dynamical timescale, clearing a path for the GRB. The material which is centrifugally supported forms an accretion disk.

A strong magnetic field ($B > 10^{14}$ G) permeates the plasma around the BH. The BH spins rapidly, pulling along the magnetic field. The infalling plasma, forming the accretion disk, cannot keep up with the rotation of the BH and the Blandford-Znajek (BZ) mechanism sets in. The Poynting flux is directed towards the rotational axis, but, the average Poynting flux is parallel to it, thus, a jet is launched in the rotational axis direction, which, as mentioned above, has lower density. Eventually, the BZ mechanism deposits so much energy in the disk that it explodes as a hypernova (HN).

3. SYNCHRONIZATION TIMESCALES

Tidal-synchronization: From Zahn (1975) and Zahn (1977) we know that the dynamical-tide-induced-synchronization timescale and equilibrium-tide synchronization timescales are

$$\tau_{DT} \propto \left(\frac{a}{R}\right)^{17/2} \quad \text{and} \quad \tau_{ET} \propto \left(\frac{a}{R}\right)^6, \quad (1)$$

respectively, where a is the orbital separation and R is the stellar radius.

For the Case-C-mass-transfer binary progenitors of GRBs we propose here, these synchronization timescales translate to a few thousand years (see, e.g.,

Final B Field [Gauss]	$\tau_{A,He}$ [Seconds]	$\tau_{A,C}$ [Seconds]	$\tau_{A,Fe}$ [Seconds]
10^{15}	5.5×10^4	2.5×10^3	1
10^{12}	5.5×10^7	2.5×10^6	10^3
10^{10}	5.5×10^9	2.5×10^8	10^5

TABLE 2

ALFVÉN TIMESCALES FOR THE HELIUM, CARBON AND IRON SHELLS ESTIMATED FOR FOSSIL MAGNETIC FIELDS THREADING THE STAR SUCH THAT THE MAGNETIC FIELD AROUND THE COMPACT OBJECT BECOMES THAT OF THE FIRST COLUMN AFTER CORE COLLAPSE.

van den Heuvel & Yoon 2007), or about the time left before GCC.

Alfvén: From Jackson (1967, Classical Electrodynamics) we know the Alfvén timescale is:

$$\tau_A = \frac{R_c \sqrt{4\pi\rho}}{B}, \quad (2)$$

here R_c is the radius of the core, ρ is the density and B is the magnetic field that threads the core.

4. GENERATING A MAGNETAR STRENGTH FIELD DURING CORE COLLAPSE

From

$$E_B = uV = \left(\frac{B^2}{8\pi}\right) \left(\frac{4\pi R_c^3}{3}\right), \quad (3)$$

(E_B is the energy, u is the energy density and V is the collapsed-core volume of radius R_c where the BZ mechanism will be active; see Moreno Méndez 2013, ApJ submitted) one can easily estimate that the energy required to produce a magnetar-strength magnetic field is between 10^{-4} and 10^{-7} times the energy available during the GCC and the end of the GRB/HN phase. Thus it is not unlikely that the BZ-required magnetic fields may be generated at this late stage.

5. CONCLUSIONS

It has been shown that a massive star in a binary that undergoes Case-C mass transfer, a common envelope and tidal synchronization may retain most of the core angular momentum gained through tidal interactions if the magnetic field threading the stellar core and the He envelope is around 100 G. Furthermore, a magnetar-like field, 10^{15} G, may be easily produced during core collapse (e.g., via a SASI or convective dynamos) given the large amount of available energy during this phase of stellar evolution

($\sim 10^{53}$ to 10^{54} erg, as opposed to 10^{47} to 10^{50} erg to generate the field). This scenario allows a BZ engine to power GRBs and is capable of explaining Cosmological as well as subluminal GRBs. This model also presents 7 known Galactic XRBs as relics of subluminal GRBs as well as LMC X-3 as a relic of a Cosmological GRB.

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